Global QCD Analysis, the Gluon Distribution, and High E_t Inclusive Jet Data[1]

Wu-Ki Tung
Michigan State University, E. Lansing, MI, USA

We report on an extensive global QCD analysis of new DIS and hadronic inclusive jet production data emphasizing the impact of these recent data on the determination of the gluon distribution, and on the interpretation of the high E_t jets highlighted by the CDF collaboration. This analysis results in (i) a better handle on the range of uncertainty of the gluon distribution, (ii) a new generation of CTEQ parton distributions which incorporates this uncertainty, (iii) a viable scenario for accommodating the high E_t jets in the conventional pQCD framework, and (iv) a systematic study of the sensitivity of the various hard processes to α_s and the consistency of α_s determination in global analysis.

1 Introduction

Global QCD analysis of lepton-hadron and hadron-hadron hard processes has made steady progress in testing the consistency of perturbative QCD (pQCD) with global data and in yielding increasingly detailed information on the universal parton distributions inside hadrons. The quark distributions inside the nucleon have been quite well determined from precise DIS and other processes in the last few years. Recent emphasis has therefore been mainly on the more elusive gluon, $G(x, Q)$.[1] The quantitative determination of $G(x, Q)$ is closely related to the measurement of α_s: the two quantities are strongly coupled since the gluon mediates the strong force. Direct photon production has long been regarded as potentially the most useful source of information on $G(x, Q)$. However, in recent years, it has been realized that a number of large theoretical uncertainties (e.g. significant scale dependence, and k_t broadening of initial state partons due to gluon radiation)[2,3] need to be brought under control before direct photon data can place a tight constraint on the gluon distribution.

Inclusive jet production in hadron-hadron collisions is very sensitive to α_s and $G(x, Q)$. NLO QCD calculations of jet cross-sections have reached a mature stage.[4] Many issues relating to jet definition (which is important for comparing theory with experiment) encountered in earlier stages of jet analysis have been extensively studied and are better understood. For the moderate to large E_t range, the scale dependence of the NLO inclusive jet cross section has been found to be relatively small. Recently, good data on single jet production have become available over a wide range of transverse energy, 15 GeV $< E_t <$ 450 GeV.[5] Thus, it is natural to incorporate inclusive jet data in a global QCD analysis. DIS data in the

[1]To appear in Proceedings of Workshop on *Deep Inelastic Scattering and Related Phenomenoa*, Rome, Italy, April, 1996. This work is done in collaboration with H.L. Lai, S. Kuhlmann, J. Huston, J. Owens, D. Soper, and H. Weerts. It is supported by DOE and NSF.

small-x region has steadily improved since the advent of HERA. The (x, Q) dependence of the measured structure functions is sensitive to the indirect influence of gluon since $G(x, Q)$ is about an order of magnitude larger than the quark distributions at small-x. Thus, we expect both the new jet data and the recent high precision data from the 1994 run of HERA to play an important role in placing constraints on $G(x, Q)$.

2 Global Analyses

Our global QCD analysis incorporates fixed-target DIS data [1] of BCDMS, CCFR, NMC, E665; lepton pair production (DY) data of E605, CDF; direct photon data of WA70, UA6; DY asymmetry data of NA51; W-lepton asymmetry data of CDF; in addition to the recent DIS data [6] of NMC, H1, ZEUS and the hadronic inclusive jet data [5] of CDF and D0. The total number of 1300 data points included (with $Q > 2$ GeV) cover a wide triangular region on a kinematic map with $log(1/x)$ and $logQ$ as axes which is anchored by HERA data at small $x = 10^{-4}$ in one corner and Tevatron jet data at high $Q = 450$ GeV in the other. All these processes are treated consistently in NLO pQCD.

Table 1: (a) Several series of global fits on which the physics discussions are based. "New DIS" refers to DIS data becoming available since 1995. Minimal "m" and minimal+2 "m+2" parametrizations are explained in the text; (b) New CTEQ4 parton distribution sets

Series	New DIS	Incl. Jets	param
A			m
B	x		m
C	x		m+2
CTEQ4A	x	x	m+2
Q_{cut}	x	x	m

PDF set	feature	$\alpha_s(m_z)$
CTEQ4M	$\overline{MS}$ sch.	0.116
CTEQ4D	DIS sch.	0.116
CTEQ4L	LO	0.132
CTEQ4A1-5	α_s series	.110-.122
CTEQ4HJ	Hi-Jet	0.116
CTEQ4LQ	Low Q_0	0.114

In addition to finding good fits to these data, a systematic effort has been made to investigate separately the impact of the new DIS and jet data and their mutual compatibility, and to assess the range of remaining uncertainty of the gluon distribution. To this end, several series of global fits, listed in Table 1, have been carried out to explore the influence on the gluon distribution due to (i) variation of the strong coupling $\alpha_s(M_z)$ (henceforth abbreviated simply as α_s) within the currently accepted range of 0.116 ± 0.006, (ii) choice of parametrization of the initial $G(x, Q)$ (at $Q = Q_0 = 1.6$ GeV) which we take to be either the "minimal" form [7] of CTEQ3 or a more general "minimal+2" form [7] used in CTEQ2 and recent MRS parton sets, and (iii) choice of lower cutoff in Q (referred to as Q_{cut}) of experimental data to be included in the analysis.

Details of these studies will be reported elsewhere.[7] Here we give a very brief summary of the main results. (a) By comparing the A- and B-series of fits, cf. Table 1, we found that

recent DIS data[6] of NMC, E665, H1 and ZEUS considerably narrow down parton distributions compared to the CTEQ3 and MRSA sets, especially if the *minimal* parametrization form for $G(x, Q)$ is adopted (B-series). Cf. Fig. 1; (b) By comparing the B- and C-series of fits,

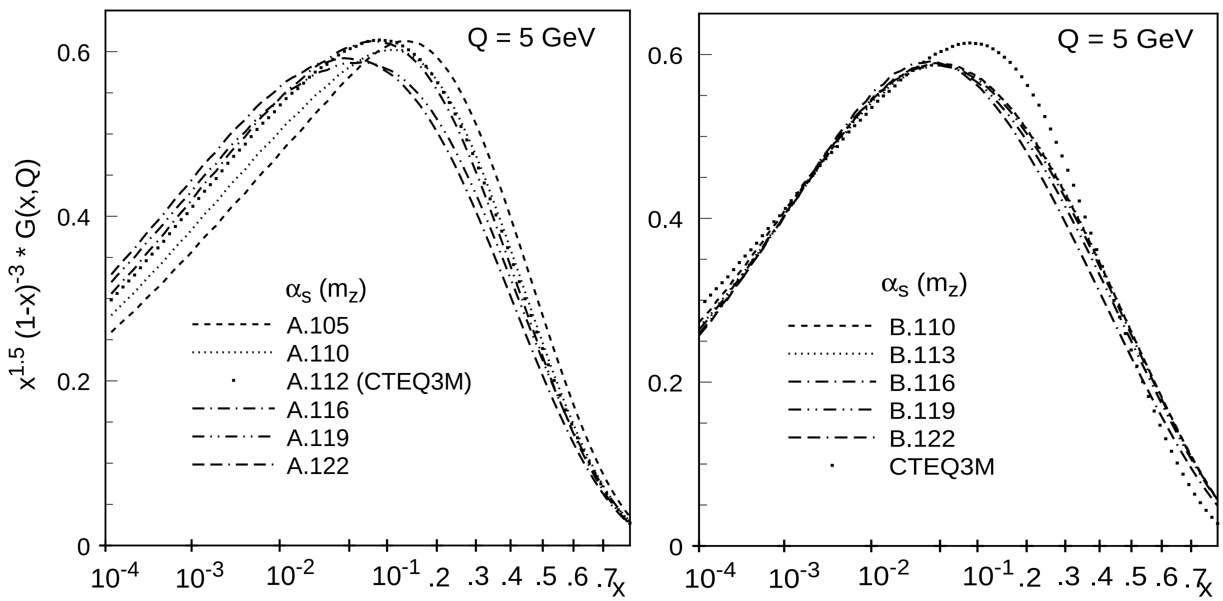

Figure 1: Comparison of gluons obtained with pre-1995 DIS data (A-series) with those using current DIS data (B-series). The "minimal" parametrization of $G(x, Q)$ is used.

we found that the new DIS data do not fully constrain $G(x, Q)$ in the more generalized parametrization (C-series); (c) By comparing the new inclusive jet data of CDF and D0 with theory predictions based on PDF's determined in the B- and C-series, we found that they agree quite well, implying an impressive consistency between the new jet production process and the others within the pQCD framework; (d) By adding the jet data to the global fit, we improve on the parton distributions found in the B- and C-series. The jet data has a significant effect in more fully constraining $G(x, Q)$ in the case of the general *(minimal+2)* parametrization compared to the C-series, cf. Fig. 2; (e) By varying the Q_{cut} we obtain the range of change in $G(x, Q)$ and found it to be less than that due to the variation in α_s.

As the result of these detailed study, we arrive at a new generation of CTEQ4 parton distributions which consists of (i) the three standard sets designated as CTEQ4M ($\overline{\text{MS}}$), CTEQ4D (DIS), and CTEQ4L (leading order); (ii) a series, CTEQ4A1-5, that gives a range of parton distributions with corresponding α_s's; and (iii) a set with a low starting value of Q, CTEQ4LQ. The CTEQ4A series represents the improved C-series mentioned in the above paragraph, cf. Table 1 and Fig. 2. These parton distributions sets give very good fits to the full range of data. The central member of the CTEQ4A series, CTEQ4A3, which gives the best overall fit is chosen to be the standard CTEQ4M. The α_s value for this set, as well as its DIS counterpart CTEQ4D, is 0.116, corresponding to $\Lambda_5 = 202$ MeV. For all these sets, $Q_0 = 1.6$ GeV, except for CTEQ4LQ which has $Q_0 = 0.7$ GeV.

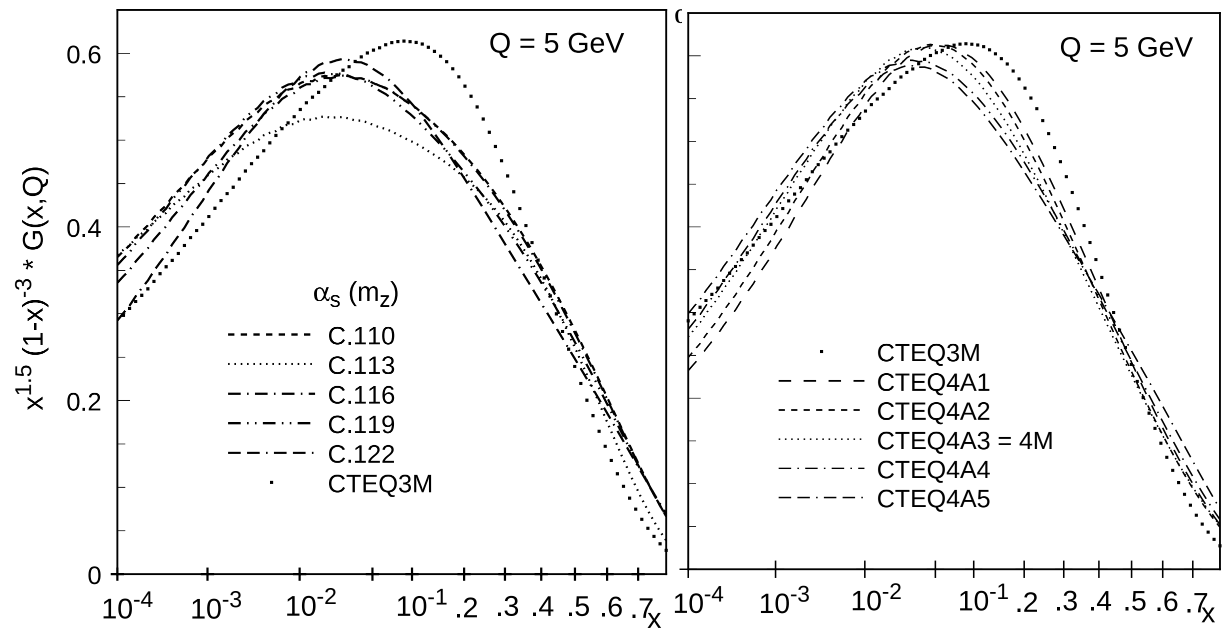

Figure 2: Comparison of gluons obtained without jet data (C-series) with those obtained with jet data (CTEQ4A series). The "minimal+2" parametrization of $G(x, Q)$ is used.

Space does not allow a presentation of the comparison between data and fits. The quality of these fits and the progress that has been made in this new round of global analysis compared to the earlier ones can be surmised from Table 2 which lists the χ^2's of some of

Table 2: Total χ^2 ($\chi^2/point$) values and their distribution among the DIS and DY experiments for current generation of parton distributions compared to previous one.

Expt.	#pts	CTEQ4M	CTEQ4HJ	MRSJ	CTEQ3M
DIS-F.T.	817	855.2(1.05)	884.3(1.08)	1024.1(1.25)	937.4(1.15)
DIS-HERA	351	362.3(1.03)	352.9(1.01)	362.0(1.03)	769.7(2.19)
DY rel.	129	102.6(0.80)	105.5(0.82)	103.6(0.80)	96.0(0.74)
Total	1297	1320	1343	1490	1803

these fits, along with other comparison parton distribution sets, for combined fixed-target and collider DIS as well as DY data sets.[2] We can see that almost all the change is caused by the improved accuracy of the HERA.

A comparison of the inclusive jet data of CDF and D0 and results of the CTEQ4M parton distribution set is given in Fig. 3a. We see that although there is a discernible rise of the CDF data above the fit curve (horizontal axis) in the high E_t region, the fit agrees with the

[2]The direct photon and jet data sets are not included in the χ^2 table since, without including the sizable theoretical uncertainties for the former and experimental systematic errors for the latter, such χ^2 values do not carry the usual statistical meaning.

D0 data within statistical errors which, in turn, agree with the CDF data within errors. We now turn specifically to this region since it has been the subject of much recent attention and speculation.

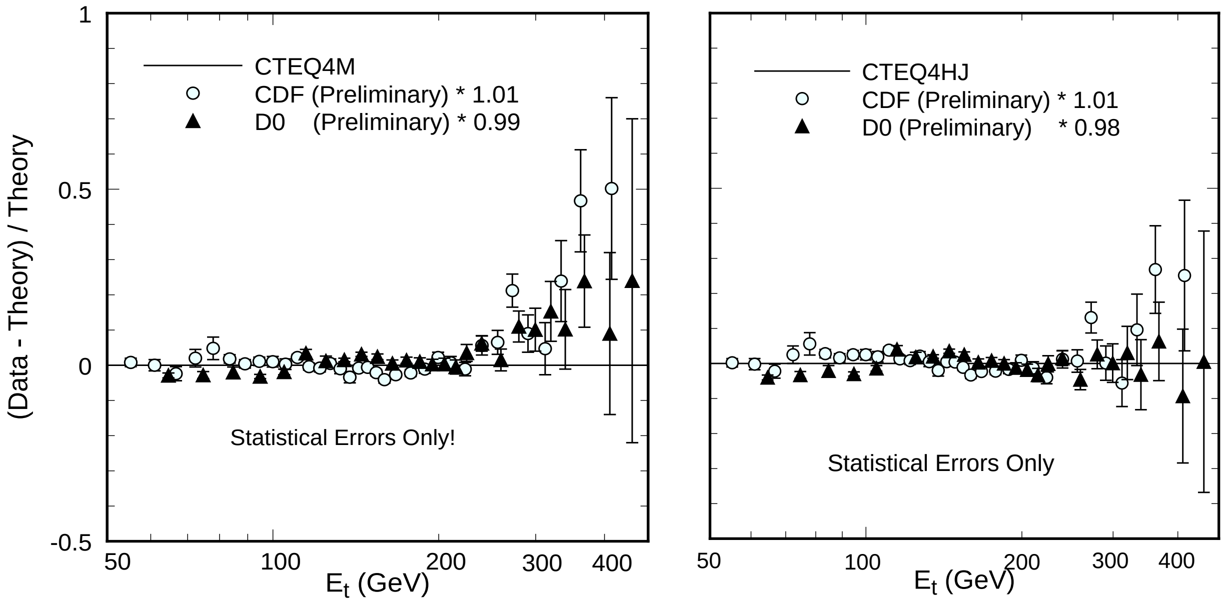

Figure 3: CDF and D0 data compared to NLO QCD using CTEQ4M and CTEQ4HJ.

3 High E_t Jets and Parton Distributions

Although inclusive jet data was included in the above-described global fits, it is understandable why the new parton distributions still under-estimates the CDF cross-section: these data points have large errors, so do not carry much statistical weight in the fitting process, and the simple (unsigned) total χ^2 is not sensitive to the pattern that the points are uniformly higher in the large E_t region. In order to address the important question of whether the CDF high E_t jet data require the presence of "new physics", we investigated the feasibility of accommodating these data in the conventional QCD framework by exploiting the flexibility of $G(x, Q)$ at higher values of x where there are few independent constraints, while maintaining good agreement with other data sets in the global analysis.[3]

To do this, it is necessary to (i) provide enough flexibility in the parametrization of $G(x, Q_0)$ to allow for behaviors different from the usual (but arbitrary) choice; and (ii) focus on the high E_t data points and assign them more statistical weight than their nominal values in order to force a better agreement between theory and experiment. Thus, the spirit of the investigation is not to obtain a "best fit" in the usual sense. Rather, it is (i) to find out whether such solutions exist; and (ii) if they do exist, to quantify how well these solutions agree with other data sets as compared to conventional parton distribution sets. The global

analysis work described in Sec. 2 without special attention to the high E_t points provides the natural setting to put the results of Ref. [3] in context.

The original study [3] was performed using the CDF Run-IA data. Fig. 3b compares predictions of one of the examples obtained, the normalization=1.0 PDF set (refer to here as CTEQ4HJ), with the more recent Run-IB results of both CDF and D0. For this comparison, an overall normalization factor of 1.01(0.98) for the CDF(D0) data set is found to be optimal in bringing agreement between theory and experiment. Results shown in Table 2 quantify the changes in χ^2 values due to the requirement of fitting the high E_t jets. Compared to the best fit CTEQ4M, the overall χ^2 for CTEQ4HJ is indeed slightly higher. But this difference is much smaller than the difference between MRSJ and CTEQ4M, and those between sets in the CTEQ4A series (not shown). Thus the price for accommodating the high E_t jets is negligible. Even though CTEQ4HJ does not give the absolute overall best fit to all data, it provides an extremely good description of all data sets. It can certainly be considered as a candidate for the gluon distribution if the other ones are.[3]

We will need strong, independent measurements of the large-x gluons in order to clarify the situation with the high-E_t jets. This poses theoretical as well as experimental challenges. As an example, in order to make effective use of existing and future direct photon production data to constrain the gluon in this region, we must understand quantitatively the observed pattern of deviation of the p_t spectrum from NLO QCD, perhaps by resummation of soft gluon effects.[2]

4 Global Analysis and α_s

The QCD coupling α_s enters all lepton-hadron and hadron-hadron processes. Hence, a global analysis of these processes places important constraints on the value of α_s and provides a comprehensive test of its universality. Because of the intimate coupling between α_s and $G(x, Q)$, the determination of α_s in global analysis is not as "clean" as in dedicated measurements such as QCD corrections to inclusive cross-sections in e^+e^- collisions or DIS sum rules. It, however, provides an important complementary way to check the consistency of the theory in a variety of different processes.

We have therefore examined the sensitivity of the various processes participating in the global analysis to the value of α_s, measured by the individual χ^2 of the relevant experiment or process, as we vary α_s over the range (0.110, 0.122). Some results are briefly summarized here. Fig. 4a shows the χ^2's of the DIS experiments and the sum of these. Clearly seen is the known preference of the fixed-target experiments for lower values of α_s in the 0.112 - 0.113 region, and the χ^2's rise rapidly for increasing α_s. On the other hand, the HERA collider data, now equally precise and numerous, show a minimum at a higher value of α_s of around 0.116-0.118. These results confirm those of the individual measurements, but in the

[3] This is to be contrasted with the conclusion of *incompatibility* between the inclusive jet and DIS data reached by Ref. [8]. Their fit to inclusive jet data over the full E_t range (the MRSJ' set) gives rise to an extremely large χ^2 (about 20,000) for the BCDMS data set.

global analysis context where the parton distributions are constrained by a much wider set of data involving many independent processes. The difference in the two preferred α_s ranges clearly needs to be better understood. It is possible, that when correlated systematic errors of the experiments are fully taken into account, this difference will become insignificant.[9] Otherwise, one must question whether there are relevant physics which has been left out. For instance, one may note that the collider data are concentrated in the small-x region; while the sensitivity to α_s of the fixed-target data are mainly in the large-x region.

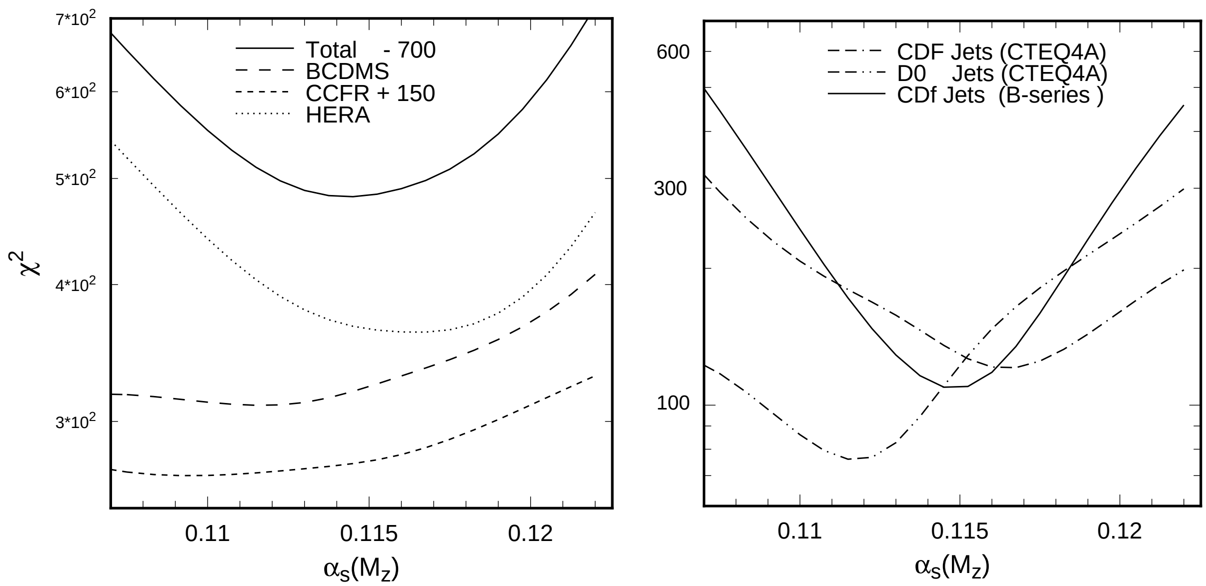

Figure 4: χ^2 vs. $\alpha_s(M_Z)$ for global fits based on current experiments: (a) BCDMS, CCFR, combined HERA collider experiments, and total of DIS+DY; (b) $\chi^2_{stat.err.only}$ of CDF and D0 jets, using CTEQ4A and B-series parton distributions.

Fig. 4b shows the nominal "χ^2" as a function of α_s for the hadronic inclusive jet data sets. The quotation marks are used here because only statistical errors are included in the calculation at this stage, it does not carry the statistical meaning of a true χ^2. This plot is presented here only for illustrative purposes because inclusive jets have been advocated in the literature as a good process to measure α_s. We note first, the apparent difference in the minima shown by the two CDF and D0 curves using CTEQ4A PDF's cannot be taken seriously. This is merely a reflection of the slight differing slopes of the respective data points seen in Fig. 3 – some E_t-dependent systematic error(s) can easily change this result. Secondly, by comparing the two CDF curves obtained using CTEQ4A and B-series PDF's respectively, one sees the minimum of the second curve is shifted from and steeper than that of the first. The reason for this lies in the fact that the constraints imposed by the jet data due to the correlation between α_s and $G(x,Q)$ are fully taken into account in CTEQ4A, but are not included in the B-series PDF's. This implies, attempted "determination of α_s" with jet data using pre-determined ("off the shelf") PDF's will very likely give unreliable values and will certainly under-estimate the errors.

5 Summary

Perturbative QCD phenomenology are very diverse; and the scale probed by current experiments spans a very wide range. The overall success of pQCD in providing a consistent framework for describing the physics of all the processes included in current global analysis is quite remarkable. We report on significant progress made in extracting the universal parton distribution functions from these analyses due to the impact of recent precision DIS and jet production data. Of the remaining uncertainties on $G(x, Q)$, those due to the value of α_s is the most significant; hence are studies in detail. The much discussed high E_t inclusive jet cross-section has been shown to be compatible with all existing data within the framework of conventional pQCD provided flexibility is given to the non-perturbative gluon distribution shape in the large-x region. Theoretical and experimental challenges to further clarify this issue are briefly mentioned.

More precise knowledge of the parton distributions, as described here, not only provides better input for the calculation of all standard model and beyond standard model processes. It provides a firmer basis for more definitive probes of the region of applicability of conventional perturbative QCD and for sharpening any potential contradictions. In this way, it opens the opportunity to explore, quantitatively, the new frontiers of QCD as well as "new physics" beyond the SM. The former are exemplified by a variety of two- or three-large scale problems which require new resummation methods much discussed in the theory community. Only by developing a credible phenomenology of these new regions of phase space, can the rich content of the quantum field theory of QCD – a theory of the largest to the smallest scales – be fully exposed.

References

1. Space limitation permits only the most directly relevant new papers be cited. See Ref.[7] for more detailed references.
2. CTEQ Collaboration: J. Huston et.al., Phys. Rev. D **51**, 6139 (1995).
3. CTEQ Collaboration: J. Huston et al., MSUHEP-50812, hep-ph/9511386, to appear in Phys. Rev. Lett.
4. S. Ellis, Z. Kunszt, and D. Soper, Phys. Rev. Lett. **64** 2121 (1990); F. Aversa et al., Phys. Rev. Lett. **65**, 401 (1990); W. Giele et al., Nucl. Phys. **B403**, 2121 (1993).
5. CDF Collaboration Run-IA: (Abe et al.), Fermilab-PUB-96/020-E (1996) to appear in Phys. Rev. Lett., and Run-IB: B. Flaugher, Talk given at APS meeting, Indianapolis, May, 1996; D0 Collaboration: G. Blazey, Rencontre de Moriond, March, 1996; D. Elvira, Rome conference on DIS and Related Phenomena, April, 1996.
6. NMC Collaboration: (M. Arneodo et al.) Phys. Lett. **B364**, 107 (1995); H1 Collaboration (S. Aid et al.): "1993 data" Nucl. Phys. **B439**, 471 (1995); "1994 data", DESY-96-039, e-Print Archive: hep-ex/9603004; ZEUS Collaboration (M. Derrick et al.): "1993 data" Z. Phys. **C65**, 379 (1995) ; "1994 data", DESY-96-076 (1996); E665

Collaboration (M.R. Adams et al.): FNAL-Pub-95/396-E, 1996.
7. For details, see H.L. Lai et al., MSUHEP-60426, hep-ph/9606399.
8. E.W.N. Glover, et.al. e-Print Archive: hep-ph/9603327.
9. This issue can be clarified by careful fits to all DIS data, incorporating fully correlated errors, such as being undertaken now by the experimental groups at HERA.